

In the United States Patent and Trademark Office

CERTIFICATE OF EXPRESS MAILING

Number: EL611001697US

Date of Deposit: February 2, 2001

SPECIFICATION

TO ALL WHOM IT MAY CONCERN:

BE IT KNOWN THAT we, Jason D. Reed, Kai Hu, Robert F. Miracky, and Claude Hilbert, have invented certain new and useful improvements in an

**APPARATUS AND METHOD FOR MICRO-ELECTROMECHANICAL SYSTEMS
TWO-DIMENSIONAL LARGE MOVEMENT ELECTROSTATIC COMB DRIVE**

APPARATUS AND METHOD FOR MICRO-ELECTROMECHANICAL SYSTEMS TWO-DIMENSIONAL LARGE MOVEMENT ELECTROSTATIC COMB DRIVE

Technical Field of the Invention:

5 The present invention relates to micro-electromechanical systems (MEMS) structures, in particular, to MEMS actuators such as MEMS comb drives.

Background of the Invention:

10 Advancement of micro-electromechanical systems (MEMS) technology and general trends toward miniaturization of devices, structures, or subsystems could significantly benefit a variety of control or communication systems. Typically, MEMS structures employed in such control or communication systems include a MEMS actuator such as a MEMS comb drive to provide displacement functionality in diverse applications including, opto-electronic communication systems, and high-speed sensor systems. When MEMS actuators are integrated with optical devices, for example, micro-optical elements such as lenses, they may provide an efficient means for manipulating a received optical beam or signal. However, integration of such a MEMS actuator with a micro-optical element or sensor system may not meet the requirements for desired displacement functionality. In addition, by simply using suitable semiconductor, substrate, and/or conductive material layers to form a multilevel layered miniature structure, it
15
20 can be difficult to provide robust and reliable MEMS actuators capable of large movements.

25 Often, deployment of MEMS actuators such as a MEMS comb drive, in an optical communication or sensor system, could allow fabrication of inexpensive and batch-fabricated integrated MEMS optical or MEMS sensor devices, respectively. Despite seemingly obvious advantages of such MEMS actuators for optical or sensor applications, systems and methods for forming these MEMS actuators that are required to meet increasingly demanding displacement functionality are desired.

 A variety of MEMS actuators generally include a stage and one or more support members such as folded suspension members or spring bars, which are devised to suspend the stage. In a

MEMS comb drive actuator, a typical stage may include one or more comb drive structures, each comb drive structure having interdigitated fingers to enable its operation responsive to an applied actuation.

5 In operation, actuation to a MEMS actuator such as a MEMS comb drive is oftentimes provided by an actuation force such as an electrostatic force being applied to either a selected comb drive structure or a particular set of comb drive structures for causing a desired displacement of the stage in a selected direction. For example, a suitable voltage bias may be applied to a first set of comb drive structures to result in the x-axis displacement of the stage in the horizontal direction.

10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
155
160
165
170
175
180
185
190
195
200
205
210
215
220
225
230
235
240
245
250
255
260
265
270
275
280
285
290
295
300
305
310
315
320
325
330
335
340
345
350
355
360
365
370
375
380
385
390
395
400
405
410
415
420
425
430
435
440
445
450
455
460
465
470
475
480
485
490
495
500
505
510
515
520
525
530
535
540
545
550
555
560
565
570
575
580
585
590
595
600
605
610
615
620
625
630
635
640
645
650
655
660
665
670
675
680
685
690
695
700
705
710
715
720
725
730
735
740
745
750
755
760
765
770
775
780
785
790
795
800
805
810
815
820
825
830
835
840
845
850
855
860
865
870
875
880
885
890
895
900
905
910
915
920
925
930
935
940
945
950
955
960
965
970
975
980
985
990
995
1000
1005
1010
1015
1020
1025
1030
1035
1040
1045
1050
1055
1060
1065
1070
1075
1080
1085
1090
1095
1100
1105
1110
1115
1120
1125
1130
1135
1140
1145
1150
1155
1160
1165
1170
1175
1180
1185
1190
1195
1200
1205
1210
1215
1220
1225
1230
1235
1240
1245
1250
1255
1260
1265
1270
1275
1280
1285
1290
1295
1300
1305
1310
1315
1320
1325
1330
1335
1340
1345
1350
1355
1360
1365
1370
1375
1380
1385
1390
1395
1400
1405
1410
1415
1420
1425
1430
1435
1440
1445
1450
1455
1460
1465
1470
1475
1480
1485
1490
1495
1500
1505
1510
1515
1520
1525
1530
1535
1540
1545
1550
1555
1560
1565
1570
1575
1580
1585
1590
1595
1600
1605
1610
1615
1620
1625
1630
1635
1640
1645
1650
1655
1660
1665
1670
1675
1680
1685
1690
1695
1700
1705
1710
1715
1720
1725
1730
1735
1740
1745
1750
1755
1760
1765
1770
1775
1780
1785
1790
1795
1800
1805
1810
1815
1820
1825
1830
1835
1840
1845
1850
1855
1860
1865
1870
1875
1880
1885
1890
1895
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105
2110
2115
2120
2125
2130
2135
2140
2145
2150
2155
2160
2165
2170
2175
2180
2185
2190
2195
2200
2205
2210
2215
2220
2225
2230
2235
2240
2245
2250
2255
2260
2265
2270
2275
2280
2285
2290
2295
2300
2305
2310
2315
2320
2325
2330
2335
2340
2345
2350
2355
2360
2365
2370
2375
2380
2385
2390
2395
2400
2405
2410
2415
2420
2425
2430
2435
2440
2445
2450
2455
2460
2465
2470
2475
2480
2485
2490
2495
2500
2505
2510
2515
2520
2525
2530
2535
2540
2545
2550
2555
2560
2565
2570
2575
2580
2585
2590
2595
2600
2605
2610
2615
2620
2625
2630
2635
2640
2645
2650
2655
2660
2665
2670
2675
2680
2685
2690
2695
2700
2705
2710
2715
2720
2725
2730
2735
2740
2745
2750
2755
2760
2765
2770
2775
2780
2785
2790
2795
2800
2805
2810
2815
2820
2825
2830
2835
2840
2845
2850
2855
2860
2865
2870
2875
2880
2885
2890
2895
2900
2905
2910
2915
2920
2925
2930
2935
2940
2945
2950
2955
2960
2965
2970
2975
2980
2985
2990
2995
3000
3005
3010
3015
3020
3025
3030
3035
3040
3045
3050
3055
3060
3065
3070
3075
3080
3085
3090
3095
3100
3105
3110
3115
3120
3125
3130
3135
3140
3145
3150
3155
3160
3165
3170
3175
3180
3185
3190
3195
3200
3205
3210
3215
3220
3225
3230
3235
3240
3245
3250
3255
3260
3265
3270
3275
3280
3285
3290
3295
3300
3305
3310
3315
3320
3325
3330
3335
3340
3345
3350
3355
3360
3365
3370
3375
3380
3385
3390
3395
3400
3405
3410
3415
3420
3425
3430
3435
3440
3445
3450
3455
3460
3465
3470
3475
3480
3485
3490
3495
3500
3505
3510
3515
3520
3525
3530
3535
3540
3545
3550
3555
3560
3565
3570
3575
3580
3585
3590
3595
3600
3605
3610
3615
3620
3625
3630
3635
3640
3645
3650
3655
3660
3665
3670
3675
3680
3685
3690
3695
3700
3705
3710
3715
3720
3725
3730
3735
3740
3745
3750
3755
3760
3765
3770
3775
3780
3785
3790
3795
3800
3805
3810
3815
3820
3825
3830
3835
3840
3845
3850
3855
3860
3865
3870
3875
3880
3885
3890
3895
3900
3905
3910
3915
3920
3925
3930
3935
3940
3945
3950
3955
3960
3965
3970
3975
3980
3985
3990
3995
4000
4005
4010
4015
4020
4025
4030
4035
4040
4045
4050
4055
4060
4065
4070
4075
4080
4085
4090
4095
4100
4105
4110
4115
4120
4125
4130
4135
4140
4145
4150
4155
4160
4165
4170
4175
4180
4185
4190
4195
4200
4205
4210
4215
4220
4225
4230
4235
4240
4245
4250
4255
4260
4265
4270
4275
4280
4285
4290
4295
4300
4305
4310
4315
4320
4325
4330
4335
4340
4345
4350
4355
4360
4365
4370
4375
4380
4385
4390
4395
4400
4405
4410
4415
4420
4425
4430
4435
4440
4445
4450
4455
4460
4465
4470
4475
4480
4485
4490
4495
4500
4505
4510
4515
4520
4525
4530
4535
4540
4545
4550
4555
4560
4565
4570
4575
4580
4585
4590
4595
4600
4605
4610
4615
4620
4625
4630
4635
4640
4645
4650
4655
4660
4665
4670
4675
4680
4685
4690
4695
4700
4705
4710
4715
4720
4725
4730
4735
4740
4745
4750
4755
4760
4765
4770
4775
4780
4785
4790
4795
4800
4805
4810
4815
4820
4825
4830
4835
4840
4845
4850
4855
4860
4865
4870
4875
4880
4885
4890
4895
4900
4905
4910
4915
4920
4925
4930
4935
4940
4945
4950
4955
4960
4965
4970
4975
4980
4985
4990
4995
5000
5005
5010
5015
5020
5025
5030
5035
5040
5045
5050
5055
5060
5065
5070
5075
5080
5085
5090
5095
5100
5105
5110
5115
5120
5125
5130
5135
5140
5145
5150
5155
5160
5165
5170
5175
5180
5185
5190
5195
5200
5205
5210
5215
5220
5225
5230
5235
5240
5245
5250
5255
5260
5265
5270
5275
5280
5285
5290
5295
5300
5305
5310
5315
5320
5325
5330
5335
5340
5345
5350
5355
5360
5365
5370
5375
5380
5385
5390
5395
5400
5405
5410
5415
5420
5425
5430
5435
5440
5445
5450
5455
5460
5465
5470
5475
5480
5485
5490
5495
5500
5505
5510
5515
5520
5525
5530
5535
5540
5545
5550
5555
5560
5565
5570
5575
5580
5585
5590
5595
5600
5605
5610
5615
5620
5625
5630
5635
5640
5645
5650
5655
5660
5665
5670
5675
5680
5685
5690
5695
5700
5705
5710
5715
5720
5725
5730
5735
5740
5745
5750
5755
5760
5765
5770
5775
5780
5785
5790
5795
5800
5805
5810
5815
5820
5825
5830
5835
5840
5845
5850
5855
5860
5865
5870
5875
5880
5885
5890
5895
5900
5905
5910
5915
5920
5925
5930
5935
5940
5945
5950
5955
5960
5965
5970
5975
5980
5985
5990
5995
6000
6005
6010
6015
6020
6025
6030
6035
6040
6045
6050
6055
6060
6065
6070
6075
6080
6085
6090
6095
6100
6105
6110
6115
6120
6125
6130
6135
6140
6145
6150
6155
6160
6165
6170
6175
6180
6185
6190
6195
6200
6205
6210
6215
6220
6225
6230
6235
6240
6245
6250
6255
6260
6265
6270
6275
6280
6285
6290
6295
6300
6305
6310
6315
6320
6325
6330
6335
6340
6345
6350
6355
6360
6365
6370
6375
6380
6385
6390
6395
6400
6405
6410
6415
6420
6425
6430
6435
6440
6445
6450
6455
6460
6465
6470
6475
6480
6485
6490
6495
6500
6505
6510
6515
6520
6525
6530
6535
6540
6545
6550
6555
6560
6565
6570
6575
6580
6585
6590
6595
6600
6605
6610
6615
6620
6625
6630
6635
6640
6645
6650
6655
6660
6665
6670
6675
6680
6685
6690
6695
6700
6705
6710
6715
6720
6725
6730
6735
6740
6745
6750
6755
6760
6765
6770
6775
6780
6785
6790
6795
6800
6805
6810
6815
6820
6825
6830
6835
6840
6845
6850
6855
6860
6865
6870
6875
6880
6885
6890
6895
6900
6905
6910
6915
6920
6925
6930
6935
6940
6945
6950
6955
6960
6965
6970
6975
6980
6985
6990
6995
7000
7005
7010
7015
7020
7025
7030
7035
7040
7045
7050
7055
7060
7065
7070
7075
7080
7085
7090
7095
7100
7105
7110
7115
7120
7125
7130
7135
7140
7145
7150
7155
7160
7165
7170
7175
7180
7185
7190
7195
7200
7205
7210
7215
7220
7225
7230
7235
7240
7245
7250
7255
7260
7265
7270
7275
7280
7285
7290
7295
7300
7305
7310
7315
7320
7325
7330
7335
7340
7345
7350
7355
7360
7365
7370
7375
7380
7385
7390
7395
7400
7405
7410
7415
7420
7425
7430
7435
7440
7445
7450
7455
7460
7465
7470
7475
7480
7485
7490
7495
7500
7505
7510
7515
7520
7525
7530
7535
7540
7545
7550
7555
7560
7565
7570
7575
7580
7585
7590
7595
7600
7605
7610
7615
7620
7625
7630
7635
7640
7645
7650
7655
7660
7665
7670
7675
7680
7685
7690
7695
7700
7705
7710
7715
7720
7725
7730
7735
7740
7745
7750
7755
7760
7765
7770
7775
7780
7785
7790
7795
7800
7805
7810
7815
7820
7825
7830
7835
7840
7845
7850
7855
7860
7865
7870
7875
7880
7885
7890
7895
7900
7905
7910
7915
7920
7925
7930
7935
7940
7945
7950
7955
7960
7965
7970
7975
7980
7985
7990
7995
8000
8005
8010
8015
8020
8025
8030
8035
8040
8045
8050
8055
8060
8065
8070
8075
8080
8085
8090
8095
8100
8105
8110
8115
8120
8125
8130
8135
8140
8145
8150
8155
8160
8165
8170
8175
8180
8185
8190
8195
8200
8205
8210
8215
8220
8225
8230
8235
8240
8245
8250
8255
8260
8265
8270
8275
8280
8285
8290
8295
8300
8305
8310
8315
8320
8325
8330
8335
8340
8345
8350
8355
8360
8365
8370
8375
8380
8385
8390
8395
8400
8405
8410
8415
8420
8425
8430
8435
8440
8445
8450
8455
8460
8465
8470
8475
8480
8485
8490
8495
8500
8505
8510
8515
8520
8525
8530
8535
8540
8545
8550
8555
8560
8565
8570
8575
8580
8585
8590
8595
8600
8605
8610
8615
8620
8625
8630
8635
8640
8645
8650
8655
8660
8665
8670
8675
8680
8685
8690
8695
8700
8705
8710
8715
8720
8725
8730
8735
8740
8745
8750
8755
8760
8765
8770
8775
8780
8785
8790
8795
8800
8805
8810
8815
8820
8825
8830
8835
8840
8845
8850
8855
8860
8865
8870
8875
8880
8885
8890
8895
8900
8905
8910
8915
8920
8925
8930
8935
8940
8945
8950
8955
8960
8965
8970
8975
8980
8985
8990
8995
9000
9005
9010
9015
9020
9025
9030
9035
9040
9045
9050
9055
9060
9065
9070
9075
9080
9085
9090
9095
9100
9105
9110
9115
9120
9125
9130
9135
9140
9145
9150
9155
9160
9165
9170
9175
9180
9185
9190
9195
9200
9205
9210
9215
9220
9225
9230
9235
9240
9245
9250
9255
9260
9265
9270
9275
9280
9285
9290
9295
9300
9305
9310
9315
9320
9325
9330
9335
9340
9345
9350
9355
9360
9365
9370
9375
9380
9385
9390
9395
9400
9405
9410
9415
9420
9425
9430
9435
9440
9445
9450
9455
9460
9465
9470
9475
9480
9485
9490
9495
9500
9505
9510
9515
9520
9525
9530
9535
9540
9545
9550
9555
9560
9565
9570
9575
9580
9585
9590
9595
9600
9605
9610
9615
9620
9625
9630
9635
9640
9645
9650
9655
9660
9665
9670
9675
9680
9685
9690
9695
9700
9705
9710
9715
9720
9725
9730
9735
9740
9745
9750
9755
9760
9765
9770
9775
9780
9785
9790
9795
9800
9805
9810
9815
9820
9825
9830
9835
9840
9845
9850
9855
9860
9865
9870
9875
9880
9885
9890
9895
9900
9905
9910
9915
9920
9925
9930
9935
9940
9945
9950
9955
9960
9965
9970
9975
9980
9985
9990
9995
10000
10005
10010
10015
10020
10025
10030
10035
10040
10045
10050
10055
10060
10065
10070
10075
10080
10085
10090
10095
10100
10105
10110
10115
10120
10125
10130
10135
10140
10145
10150
10155
10160
10165
10170
10175
10180
10185
10190
10195
10200
10205
10210
10215
10220
10225
10230
10235
102

deformations of support members in a MEMS actuator based integrated device; it is desirable to devise the MEMS actuator with appropriate structural, electrical, and operational characteristics.

FIG. 1A is a top plan view of a prior art MEMS unidirectional comb drive 100. MEMS unidirectional comb drive 100 is useful in explaining an exemplary embodiment of the invention, as described later in the context of a bi-directional comb drive. MEMS unidirectional comb drive 100 may comprise a shuttle 105, the movable portion, and a stator 110, the anchor portion. Shuttle 105 may include a spring 115 comprising a horizontal bar 120 and a vertical bar 125. Shuttle 105 and stator 110 may be anchored at anchors 130A and 130B, respectively. MEMS unidirectional comb drive 100 may include a set of interdigitated fingers for selectively positioning shuttle 105 responsive to an appropriate actuation force. The actuation force may cause a controlled displacement of shuttle 105 relative to stator 110. Such displacement enables a selective orientation of MEMS unidirectional comb drive 100 at a desired position, which may be generally determined by the amount of displacement, in response to the actuation. Spring 115 could be devised of a desired geometry to generally provide a particular range of displacement responsive to a specific type of actuation force such as an electrostatic force. For example, a voltage bias may be applied between shuttle 105 and stator 110.

In the illustrated exemplary embodiment of FIG. 1A, shuttle 105 having a shuttle anchor side 132 comprises a first set of fingers 135A through 135D. Likewise, stator 110 having a stator anchor side 137 comprises a second set of fingers 140A through 140C. Both the first and second set of fingers 135A through 135D and 140A through 140C are advantageously configured in an interlocked manner. Spring 115 may be coupled between shuttle anchor side 132 and anchor 130A. More specifically, horizontal bar 120 may be fixedly coupled to shuttle anchor side 132 and vertical bar 125 may be fixedly connected to anchor 130A. For stator 110, stator anchor side 137 may be adapted to fixedly connect to anchor 130B.

In operation, MEMS unidirectional comb drive 100 may be selectively displaced responsive to an actuation being applied in the form of an electrostatic force. With continuing reference to FIG. 1A, MEMS unidirectional comb drive 100 could be actuated to move in a x-direction as indicated by a horizontal arrow 142. More specifically, when a voltage bias is

applied between the moving part (shuttle 105) and the anchor part (stator 110), the electrostatic force generated from the applied voltage bias will drive the comb drive 100 to move in the x-direction. The amount of displacement is generally determined by balancing the electrostatic force and spring reaction force according to the relationship as shown below in equation 1.

5 (1)
$$F = -\frac{\partial U}{\partial x} = \frac{N\epsilon V^2}{2d} = kx$$

Where: V is the applied voltage bias, x the shuttle displacement, N the number of fingers, k the stiffness of the spring(s), ϵ the air permittivity, and d the gap of fingers (as shown in FIG. 1A).

Two significant aspects are to be noted here. First, the comb drive displacement is independent of the interlocked length (shown in the FIG. 1A as "1-x") between two combs. This is due to the fact that the electrostatic potential is linearly proportional to the interlocked length, and the force is the derived gradient of the potential, which becomes constant. Second, the displacement is inversely proportional to the stiffness "k" of the springs. In the present case, the spring is made of a long vertical and short horizontal bar. When the comb moves in x-direction, both bars will contribute to the displacement. The percentage of their contribution will, however, be quite different. It is observed that the vertical bar undergoes bending and the horizontal bar the extension. To understand the relative significance of bending and extension, we consider two bars of the same length with a spring bar cross-section of 4x4 micron, driven by 100 V bias on a comb drive of 20 fingers with the finger gap of 4 micron.

Unfortunately, in a two-dimensional comb drive it is even more difficult to avoid deformation and movement of a first set of comb drives while actuating and displacing a second set of comb drives connected to the first set of comb drives. For instance, while performing excursions using the first set of comb drives, in one direction such as the x-axis, it is highly desirable to prevent any displacement along that same axis of the second set of comb drives which may control the motion in the y-axis. Such robust MEMS actuators could operate as a building block in a variety of opto-electromechanical equipment.

Accordingly, there is a need for two-dimensional micro-electromechanical systems (MEMS) comb drive actuator, which may be controllably oriented at a desired position.

Summary of the Invention:

10 The present invention generally provides micro-electromechanical systems (MEMS) structures, in particular, MEMS actuators such as comb drives. In an exemplary embodiment, a comb drive apparatus includes a first set of comb pairs and a second set of comb pairs coupled to the first set of comb pairs. A stage may be coupled to the first and second sets of comb pairs. A first plurality of springs may be interposed between the second set of comb pairs and the stage and between the second set of comb pairs and the first set of comb pairs for movably coupling the second set of comb pairs to the stage and to the first set of comb pairs. Likewise, a second plurality of springs may be interposed between the first set of comb pairs and the stage and between the first set of comb pairs and the second set of comb pairs for movably coupling the first set of comb pairs to the stage and to the second set of comb pairs.

15 The stage may be suspended, electrically conductive, and mechanically operable to permit a controlled displacement thereof in first and second directions responsive to respective first and second actuating forces such as electrostatic forces of appropriate bias. The first actuation force to the first set of comb pairs may provide a first displacement to the stage in the first direction, and the second actuation force to the second set of comb pairs may provide a second displacement to the stage in the second direction. The first actuation force may cause a bending of the first plurality of springs while the second plurality of springs being maintained substantially straight to provide the first displacement. The second actuation force may cause a bending of the second plurality of springs while the first plurality of springs being maintained substantially straight to provide the second displacement.

20 Each spring of the first plurality of springs may be disposed in a first orientation and each spring of the second plurality of springs may be disposed in a second orientation being substantially orthogonal to the first orientation. In addition, each spring of the first and second pluralities of springs could be formed as a bar.

25 In an another embodiment, a comb drive apparatus includes a first set of comb pairs, a second set of comb pairs coupled to the first set of comb pairs, and a suspended stage coupled to the first and second sets of comb pairs. Each comb pair of the first set of comb pairs having a

first fixed comb and a first movable comb. The first movable comb may include first and second ends being connected by a first support. Each comb pair of the second set of comb pairs having a second fixed comb and a second movable comb. The second movable comb may include first and second ends being connected by a second support.

5 Each first spring of the first and second pluralities of first springs having a first end and a second end. The first ends of the first plurality of first springs being connected to the suspended stage and the second ends of the first plurality of first springs being connected to the respective second support of the second movable combs. And the first ends of the second plurality of first springs being connected to the respective first movable comb and the second ends of the second plurality of first springs being connected to the respective first end or second end of the second movable combs, thereby movably coupling the second set of comb pairs to the suspended stage and to the first set of comb pairs.

10 Each second spring of the first and second pluralities of second springs having a first end and a second end. The first ends of the first plurality of second springs being connected to the suspended stage and the second ends of the first plurality of second springs being connected to the respective first support of the first movable combs. And the first ends of the second plurality of second springs being connected to the respective second movable comb and the second ends of the second plurality of second springs being connected to the respective first end or second end of the first movable combs, thereby movably coupling the first set of comb pairs to the
15 suspended stage and to the second set of comb pairs.

20 In operation, said first set of comb pairs may provide a first displacement to the suspended stage in a first direction in response to a first electrostatic force. The second set of comb pairs may provide a second displacement to the suspended stage in a second direction in response to a second electrostatic force. The first electrostatic force may cause a controlled
25 bending of the first and second pluralities of first springs for displacing the first movable combs while the first and second pluralities of second springs being maintained substantially straight for preventing displacement of the second movable combs. The second electrostatic force may cause a controlled bending of the first and second pluralities of second springs for displacing the

second movable combs while the first and second pluralities of first springs being maintained substantially straight for preventing displacement of the first movable combs.

In an another alternate exemplary embodiment, a micro-electromechanical apparatus including first, second, third, and fourth comb drives, the first comb drive being disposed spatially opposite to the second comb drive and the third comb drive being disposed spatially opposite to the fourth comb drive, each comb drive including: a fixed comb having a first set of fingers; a movable comb having a first end, second end, support, and a second set of fingers arranged in an interdigitated manner with the first set of fingers; and first, second, and third springs coupled to the movable comb to said first end, said second end, and said support, respectively, wherein the movable comb being suspended by the first, second, and third springs for providing a displacement thereof relative to the fixed comb in response to an actuating force being applied between the fixed comb and the movable comb.

In an another alternate exemplary embodiment, a micro-electromechanical comb drive including first, second, third, and fourth comb drives, the first comb drive being spatially disposed opposite to the second comb drive and the third comb drive being spatially disposed opposite to the fourth comb drive, each comb drive including: a fixed electrode; a movable electrode disposed spatially opposite to the fixed electrode; and a plurality of spring bars coupled to the movable electrode, the plurality of spring bars being selectively oriented responsive to an actuating force being applied between the fixed and movable electrodes.

In an another alternate exemplary embodiment, a micro-electromechanical actuator including first, second, third, and fourth drives, the first drive being spatially disposed opposite to the second drive and the third drive being spatially disposed opposite to the fourth drive, each drive including: a fixed portion a movable portion; and a spring structure formed to suspend the movable portion, the spring structure displaces the movable portion relative to the fixed portion in response to an actuating force being applied between the fixed portion and the movable portion.

In an another alternate exemplary embodiment, a two-dimensional comb drive apparatus including a set of horizontal comb pairs, each of the horizontal comb pair having a horizontal fixed comb and a horizontal movable comb, the horizontal movable comb including first and second ends being connected by a horizontal support; a set of vertical comb pairs coupled to the set of horizontal comb pairs, each of the vertical comb pair having a vertical fixed comb and a vertical movable comb, the vertical movable comb including first and second ends being connected by a vertical support; a suspended stage coupled to the sets of horizontal and vertical comb pairs; first and second pluralities of horizontal springs, each horizontal spring having a first end and a second end, the first ends of the first plurality of horizontal springs being connected to the suspended stage and the second ends of the first plurality of horizontal springs being connected to the respective vertical support of the vertical movable combs, and the first ends of the second plurality of horizontal springs being connected to the respective horizontal movable comb and the second ends of the second plurality of horizontal springs being connected to the respective first end or second end of the vertical movable combs, thereby movably coupling the set of vertical comb pairs to the suspended stage and to the set of horizontal comb pairs; and first and second pluralities of vertical springs, each vertical spring having a first end and a second end, the first ends of the first plurality of vertical springs being connected to the suspended stage and the second ends of the first plurality of vertical springs being connected to the respective horizontal support of the horizontal movable combs, and the first ends of the second plurality of vertical springs being connected to the respective vertical movable comb and the second ends of the second plurality of vertical springs being connected to the respective first end or second end of the horizontal movable combs, thereby movably coupling the set of horizontal comb pairs to the suspended stage and to the set of vertical comb pairs.

In an another alternate exemplary embodiment, a method for forming a two-dimensional comb drive, comprising: providing a first set of comb pairs; providing a second set of comb pairs coupled to the first set of comb pairs; providing a stage coupled to the sets of first and second comb pairs; providing a first plurality of springs interposed between the second set of comb pairs and the stage and between the second set of comb pairs and the first set of comb pairs for

movably coupling the second set of comb pairs to the stage and to the first set of comb pairs; and providing a second plurality of springs interposed between the first set of comb pairs and the stage and between the first set of comb pairs and the second set of comb pairs for movably coupling the first set of comb pairs to the stage and to the second set of comb pairs.

5 The foregoing has outlined rather broadly the features and technical advantages of the present invention in order that the detailed description of the invention that follows may be better understood. Additional features and advantages of the invention will be described hereinafter which form the subject of the claims of the invention. It should be appreciated by those skilled in the art that the conception and specific embodiment disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present invention. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the invention as set forth in the appended claims.

Brief Description of the Drawings:

For a more complete understanding of the present invention and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

FIG. 1A is a top plan view of a prior art micro-electromechanical systems (MEMS) unidirectional comb drive.

FIG. 1B is a graph of exemplary displacements due to bending and extension for a MEMS comb drive.

FIG. 2A is a top plan view of an exemplary embodiment of a MEMS fully suspended bi-directional comb drive consistent with one aspect the present invention.

FIG. 2B is a top plan view of the MEMS fully suspended bi-directional comb drive of FIG. 2A actuated in x-axis (horizontal direction) in accordance with one aspect of the present invention.

FIG. 3 is a graph of an exemplary variation of displacements for the MEMS fully suspended bi-directional comb drive of FIG. 4A with different spring lengths.

FIG. 4A is a top plan view of an exemplary MEMS inter-linked bi-directional comb drive.

FIG. 4B is a top plan view of an exemplary MEMS nested bi-directional comb drive.

FIG. 5 is a top plan view of an exemplary embodiment of a MEMS fully suspended bi-directional comb drive actuator for optical applications consistent with one aspect the present invention.

FIG. 6A is a top plan view of the MEMS fully suspended bi-directional comb drive actuator of FIG. 5 actuated in x-axis (horizontal direction).

FIG. 6B is a top plan view of the MEMS fully suspended bi-directional comb drive actuator of FIG. 5 actuated concurrently in x-axis (horizontal direction) and y-axis (vertical direction).

FIG. 7A is a top plan view of another exemplary embodiment of a MEMS fully suspended bi-directional comb drive actuator for optical applications in accordance with one aspect the present invention.

FIG. 7B is a top plan view of the MEMS fully suspended bi-directional comb drive
5 actuator of FIG. 7A actuated in y-axis (vertical direction).

Detailed Description

A Micro-electromechanical systems (MEMS) actuator such as a MEMS comb drive generally comprises comb pairs, each comb pair may include a fixed comb and a movable comb coupled to a plurality of suspension members, such as springs bars, or the like. Suspension members are generally utilized to support the movable combs. Suspension members may be suitably devised to enable a controlled operation of the MEMS comb drive. An actuation force such as an electrostatic force may be selectively applied to the comb pairs for orienting the MEMS comb drive at a desired position. The present invention is generally directed to such MEMS comb drives, which could be utilized for realizing a variety of control and/or communication systems.

One exemplary embodiment of the present invention is generally described with respect to a MEMS fully suspended bi-directional comb drive, which includes suspension members as spring bars. The geometric features for the spring bars can be readily devised using a conventional photolithography based micro-fabrication process. In an exemplary embodiment, a suitable micro-fabrication technology, in a known manner, is generally employed to fabricate the chip-scale or miniature device of the present invention useful for a variety of optical applications. For example, an optical MEMS actuator may be advantageously devised to integrate with one or more micro-optical elements such as micro-lenses or micro-mirrors. The present invention should, however, not necessarily be restricted to the field of micro-optical elements and/or comb drive actuators, as will be readily evident. Like reference numerals refer to similar elements throughout the drawings.

FIG. 1B is a graph of exemplary displacements (in meters) due to bending and extension for a MEMS comb drive such as the MEMS unidirectional comb drive 100 of FIG. 1A. It is observed that the displacement due to bending is an order or two magnitudes larger than the displacement due to the extension. In fact, the displacement due to the extension can be practically neglected. This observation bears significant implications for bi-directional or two-dimensional comb drives.

FIG. 2A is a top plan view of an exemplary embodiment of a MEMS fully suspended bi-directional comb drive 200 consistent with one aspect the present invention. A relatively simple but representative design of MEMS fully suspended bi-directional comb drive 200 may comprise vertical spring bars 205A through 205L and horizontal spring bars 210A through 210H to fully suspend a movable portion without touching a fixed portion. The MEMS fully suspended bi-directional comb drive 200 may further comprise a first set of horizontal combs 212A, 212B and a second set of vertical combs 213A, 213B. Each of the first set of horizontal combs 212A, 212B includes a pair of oppositely disposed combs with one comb being movable and the other being fixed. In particular, the horizontal comb 212A includes a fixed comb 214A and a movable comb 215A.

The fixed portion may include fixed combs 214A through 214D. Likewise, the movable portion may include movable combs 215A through 215D and an inter-linked stage 220. Each movable comb 215 is generally attached by both associated horizontal and vertical spring bars. For example, movable comb 215A is attached to horizontal spring bars 210A, 210B and vertical spring bars 205B through 205E. This pattern of spring distribution is advantageously employed to exploit the bending versus extension behavior as illustrated in FIG. 1B to achieve relatively large bi-directional movement without being limited by finger spacing.

FIG. 2B is a top plan view of the MEMS fully suspended bi-directional comb drive 200 of FIG. 2A actuated in x-axis (horizontal direction 225). Thus, when the left and right combs are actuated in x-direction, the horizontal displacement will make all vertical spring bars 205A through 205L bend by approximately the same amount, but the horizontal spring bars 210A through 210H assume very little deformation since bending is the dominating deformation as opposed to extension. Therefore, the movement in top and bottom combs 215A and 215C, respectively, can be negligible (as indicated from the deformed shape in FIG. 4B). Accordingly, the movement in horizontal direction 225 is not going to cause vertical comb fingers to touch each other. Similarly, actuation in the vertical direction is not going to cause horizontal comb finger interference. Thus, MEMS fully suspended bi-directional comb drive 200 can achieve large x and y displacements without being limited by comb finger spacing. Moreover, MEMS

fully suspended bi-directional comb drive 200 has a decent form factor, enough real estate for center mass distribution, and equal participating mass in x- and y-direction actuation. It shores the advantages of both inter-linked and nested comb drives.

As persons skilled in the art will appreciate that using a typical micro-fabrication process, in a known manner, the MEMS fully suspended bi-directional comb drive 200 may be readily fabricated. For example, employing a substrate layer and a conductive layer, the MEMS fully suspended bi-directional comb drive 200 may be formed through a deposition and patterning process. In particular, the first set of horizontal combs 212A, 212B, second set of vertical combs 213A, 213B, inter-linked stage 220, and vertical spring bars 205A through 205L and horizontal spring bars 210A through 210H may be formed from a single layer. For example, a layer of polysilicon may be utilized to form the MEMS fully suspended bi-directional comb drive 200. Additionally, the vertical spring bars 205A through 205L and horizontal spring bars 210A through 210H could be suitably attached to the substrate layer to form anchors. For example, vias may be devised for anchoring the MEMS fully suspended bi-directional comb drive 200.

However, it is to be understood that the movable combs 215A through 215D of the MEMS fully suspended bi-directional comb drive 200 may or may not share the same anchors at the four corners of the structure as depicted in FIGS. 2A and 2B. For example, the vertical spring bar 205A and the horizontal spring bar 210A could be anchored separately.

In an exemplary embodiment, one-micron thick layer of polysilicon may be used as the primary composition of the single conductive layer. However, other materials or combinations of materials may be employed, which can be deposited and patterned according to a desired specification over a particular substrate layer.

In operation, a two-dimensional comb drive such as the MEMS fully suspended bi-directional comb drive 200 may be controllably oriented at a desired position responsive to an appropriate actuation. Specifically, undesired deformation and movement of the second set of vertical combs 213A, 213B while actuating and displacing the first set of horizontal combs 212A, 212B coupled to the second set of vertical combs 213A, 213B can be significantly reduced by appropriate shapes, positions, and combinations thereof for the vertical spring bars 205A

through 205L and horizontal spring bars 210A through 210H. Likewise, undesired deformation and movement of the first set of horizontal combs 212A, 212B while actuating and displacing the second set of vertical combs 213A, 213B coupled to the first set of horizontal combs 212A, 212B can also be significantly reduced. For instance, while performing excursions using the second set of vertical combs 213A, 213B, in one direction such as the x-axis, selective bending of the vertical spring bars 205A through 205L and stiffness of the horizontal spring bars 210A through 210H may prevent substantial displacement along that same axis of the movable combs 215A through 215D of the first set of horizontal combs 212A, 212B which may control the motion in the y-axis.

FIG. 3 is a graph of a range of exemplary displacements calculated for the MEMS fully suspended bi-directional comb drive 200 of FIG. 2A for different spring bar lengths. It is to be understood that as shown in FIG. 2A just straight bars may function as springs. Moreover, the MEMS fully suspended bi-directional comb drive 200 can be readily devised to provide maximum displacements in x or y directions through parametric optimization of spring pattern and spring distribution.

In an exemplary embodiment, MEMS fully suspended bi-directional comb drive 200 comprises a conductor or semi-conductor, with each pair of opposing combs having 20 to 19 interdigitated fingers. The spring bar cross-section is 3x4 microns, i.e. 3 microns thickness and 4 microns width, and the fingers are 8 microns long with a gap between fingers of 2 microns. As an example, the length of vertical spring bars 205A through 205L is devised twice the length of horizontal spring bars 210A through 210H. As shown in FIG. 3, displacements greater than 10 microns are attainable for spring bar lengths greater than 500 microns. Persons skilled in the art will recognize that such geometric features are readily achievable using generally known photolithography based micro-fabrication manufacturing processes. The foregoing describes only one embodiment of the invention and many variations of the embodiment will be obvious for a person skilled in the art of semiconductor, micro-electromechanical fabrication. Certainly, various other materials and techniques can be utilized in the construction of the various layers.

FIG. 4A is a top plan view of an exemplary MEMS inter-linked bi-directional comb drive 425. In this configuration, four exterior combs 430A through 430D (two horizontal and two vertical) are anchored, and four internal combs 435A through 435D are inter-linked via an inter-link 440. A desired movement or displacement of the inter-linked combs in x-direction as indicated by an arrow 445, can be achieved by applying an appropriate voltage between the two exterior horizontal combs 430A and 430C and the inter-linked internal combs 435A through 435D. Likewise, in y-direction as indicated by an arrow 447, a movement can be achieved by applying a suitable voltage between the two exterior vertical combs 430B and 430D and the inter-linked internal combs 435A through 435D. Among many advantages, the main advantages of the inter-linked comb drives are decent form factor (x-y dimensions can be the same), and achievable equal or similar electrostatic driving force. However, both x- and y-directional movements can be limited by a finger gap 449 (assuming all exterior and internal combs are identical in shape and size). For example, when the amount of displacement in the x-direction 445 exceeds the finger gap 449, the vertical fingers of the anchored combs 430B and 430D and movable combs 435B and 435D will touch each other, creating an electrical short. This factor could become even more exacerbated in applications where the finger gap 449 has to be small to obtain enough driving force.

FIG. 4B is a top plan view of an exemplary MEMS nested bi-directional comb drive 465. MEMS nested bi-directional comb drive 465 may include horizontal or external combs 470A, 470B and vertical or nested combs 470C and 470D. With reference to FIGS. 4A and 4B, a desired movement in the x-direction 445 can be achieved by appropriately driving horizontal combs 470A, 470B. Likewise, a movement in y-direction 447 may be achieved by suitably driving the vertical combs 470C and 470D, which are rigidly nested within the movable-part frame of horizontal combs 470A, 470B. When an external comb drive is in action and a movement in the x-direction 445 is actuated, the movable and fixed parts of the nested combs 470C and 470D moves the same amount. On the other hand, when the nested combs 470C and 470D are in action and a vertical displacement in the y-direction 447 is actuated, the external

combs 470A and 470B are fully anchored. Therefore, this design may completely eliminate the x-y motion interference. Accordingly, the displacement may not be limited by finger gap.

However, nested spring and combs generally occupy the internal spaces and reduce the real estate and flexibility for mass distribution. In addition, to achieve the same actuation force, the nested combs 470C and 470D may have to assume a geometry (e.g. comb spacing, finger size) different from the external combs 470A and 470B, thereby increasing process complexity. Moreover, the actuation mass in the x-direction 445 is different from that in the y-direction 447, as the movement in the x-direction 445 carries the complete nested combs 470C and 470D, but the movement in y-direction 447 only moves the external combs 470A and 470B.

FIG. 5 is a top plan view of an exemplary embodiment of a MEMS fully suspended bi-directional actuator 500 consistent with one aspect of the present invention. The MEMS fully suspended bi-directional actuator 500 may comprise a micro-frame 503 to receive a micro-optical element such as a micro-lens or a micro-mirror and comb drives 505A through 505D. Each comb drive includes a fixed comb configured in interdigitated fashion with an associated movable drive. For example, comb drives 505A through 505D each comprise a fixed comb 510, 510A through 510D, and an associated movable comb 515, 515A through 515D, respectively. In shown embodiment of FIG. 5, the comb drives 505A through 505D are identical. However, different sizes, shapes or forms of comb drives 505A through 505D could be devised. Moreover, micro-frame 503 may be devised to connect with movable combs 515A through 515B via spring bars 520A through 520D.

Each movable comb, 515A through 515D may include first and second ends extended longitudinally for fixedly connecting the movable comb to a substrate 525, thereby suspending the MEMS fully suspended bi-directional actuator 500. To couple fixed combs 510A through 510D to the substrate 525, anchors 530A through 530D, respectively, may be utilized. However, it should be appreciated that fixed combs 510A through 510D may be coupled differently to the substrate 525. Each comb drive 505 may include a set of interdigitized fingers. More specifically, each fixed and movable combs 510, 515 may comprise a plurality of fingers to form the set of interdigitized fingers. For example, fixed comb 510A may include a first set of fingers

535A and movable comb 515A may include a second set of fingers 540A. As shown in FIG. 5, the first set of fingers 535A could include nineteen fingers with each finger having 10 microns of width and generally interposed at 8 microns in separation from the adjacent finger. Moreover, fingers may comprise a metal layer.

5 It is to be understood that the MEMS fully suspended bi-directional actuator 500 may be fabricated with MEMS technology generally utilizing a known surface micro-machining manufacturing process. The depicted actuator 500 could be advantageously utilized for a variety of optical applications. For example, micro-optics can be readily integrated with the actuator 500 to enable optical communications. In one embodiment, a micro-lens may be disposed in the micro-frame 503 for manipulating any optical signals projected therethrough.

10 In operation, MEMS fully suspended bi-directional actuator 500 may selectively micro-position the micro-lens in response to an actuating force such as an electrostatic force being applied through an actuation voltage. When an appropriate actuation voltage is placed across either the first and second set of fingers 535A, 540A, an electrostatic charge may be generated therebetween. In turn, movable comb 515A may be displaced. For example, when the comb drive 505A may be actuated, first movable comb 515A may be pulled towards the associated fixed comb 510A. In one embodiment, actuation voltage of 50 Volts is used for providing a maximum displacement of 5 microns.

15 FIG. 6A is a top plan view of the MEMS fully suspended bi-directional comb drive actuator 500 of FIG. 5 actuated in x-axis (horizontal direction). A pre-actuated position of the actuator 500 is indicated by a dotted structure 605. Upon proper actuation, a portion of the MEMS fully suspended bi-directional comb drive actuator 500 is displaced. A post-actuated position of the actuator 500 is illustrated by a stretched structure 610.

20 FIG. 6B is a top plan view of the MEMS fully suspended bi-directional comb drive actuator 500 of FIG. 5 actuated concurrently in x-axis (horizontal direction) and y-axis (vertical direction). A pre-actuated position of the actuator 500 is depicted by a dotted structure 650. When appropriately actuated, a portion of the MEMS fully suspended bi-directional comb drive actuator 500 is displaced. Accordingly, a post-actuated position of the actuator 500 is illustrated

by a moved structure 655. With reference to FIGS. 6A and 6B, displacements of more than 10 microns may be readily attainable. It should be appreciated that significantly larger displacements could be achieved with finer geometric features, even at a reduced spring length.

FIG. 7A is a top plan view of another exemplary embodiment of a MEMS fully suspended bi-directional comb drive actuator 700 for optical applications in accordance with one aspect the present invention. MEMS fully suspended bi-directional comb drive actuator 700 may include an array of micro-frames 705. FIG. 7B is a top plan view of the MEMS fully suspended bi-directional comb drive actuator 700 of FIG. 7A actuated in y-axis (vertical direction). A pre-actuated position of the actuator 700 is indicated by a dotted structure 750. Upon proper actuation, a portion of the MEMS fully suspended bi-directional comb drive actuator 700 is displaced. A post-actuated position of the actuator 700 is illustrated by a stretched structure 755.

Accordingly, an apparatus and method for a micro-electromechanical systems (MEMS) actuator such as a MEMS two-dimensional electrostatic comb drive having springs being advantageously configured to provide relatively large movements in first and second directions is generally disclosed. In response to an appropriate electrostatic actuation force being applied to the MEMS two-dimensional electrostatic comb drive, the springs enable controlled displacement along both x-axis (horizontal direction) and y-axis (vertical direction).

Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made to the embodiments herein without departing from the spirit and scope of the invention as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the disclosure of the present invention, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the present

invention. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.

We claim:

1623695.8